

Marine Research Sub-Programme  
(NDP 2007–'13) Series



# Development of an Efficient Design Technique for the Optimisation of Mooring Systems for Wave Energy Arrays

Industry-Led Award, Final Report



*Lead Partner: MCS Kenny Ltd.*

*Authors: Padraic Kirrane,  
Paul Fabricius, Remi Morvan*

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# Marine Research Sub-Programme 2007-2013

## *Industry-Led Award*

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### ***Development of an Efficient Design Technique for the Optimisation of Mooring Systems for Wave Energy Arrays***

*(Project Reference: ILA/07/005)*

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Lead Partner:	MCS Kenny Ltd.
Authors:	Padraic Kirrane, Paul Fabricius, Remi Morvan
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## I. PROJECT SUMMARY

MCS Kenny has carried out research funded by the Marine Institute on mooring systems for wave energy arrays as part of its ongoing research and development programme. This project built upon MCS Kenny's core competency in riser system design and was envisaged as contributing to the company's new business development activity.

The objectives of this research were:

1. To review the wave energy industry and define design parameters;
2. To establish a comprehensive set of design curves to facilitate the selection of a preliminary mooring system;
3. To develop trends in system response from the evaluation of a broad range of Wave Energy Converter (WEC) specifications, water depths and environments;
4. To assess the fatigue life of wave energy mooring configurations;
5. To prepare a preliminary Integrity Management Strategy (IMS) for wave energy mooring system arrays; and
6. To integrate all progress into a guideline document.

Various software packages supported the project and are described in Appendix II; hydrodynamic analysis of various cylinders representing a range of WECs was performed using Wamit; mooring analysis was performed using Ariane-3Dynamic and Flexcom.

From the analysis, a comprehensive set of design curves was compiled for a range of WEC sizes, water depths, mooring configurations and layouts, and environmental conditions. These curves allow identification of feasible configurations for a given set of design parameters.

A preliminary Integrity Management Strategy (IMS) was compiled to ensure the safe operation and station-keeping of WECs in a mooring system array. The IMS included a risk assessment to identify potential failures, a risk assessment and an inspection/monitoring strategy to mitigate these risks.

Through this project, the company gained valuable experience in the design of wave energy mooring system arrays and is now in a key position to help researchers and developers, to bring their WECs to full scale commercialization. In doing so, new business opportunities for MCS Kenny will be realised.

Environmental conditions representative of the Irish coast have been selected for the assessment in water depths ranging from 50m to 200m, which exist up to 200km offshore Ireland. It is considered unlikely that wave energy devices will be installed beyond this distance offshore.

Six mooring configurations were considered; these are listed below and illustrated in Appendix III:

- Catenary Configuration
- Catenary with Rope
- Surface Buoy Configuration
- Surface Buoy with Clump Weight
- Compliant Configuration
- Surface Buoy Configuration with Vertically Loaded Anchors

WECs are a relatively new concept and not yet widely used as a source of power generation. Few industry standards or design codes exist regarding the mooring of such devices. The current 'state of art' of current industry design approach is discussed. It is based on MCS Kenny's extensive experience in the area of mooring design and on discussions with industry. This study compares design codes and recommended practices prepared by API (American Petroleum Institute), DNV (Det Norske Veritas) and BV (Bureau Veritas), relevant to wave energy mooring systems.

Prototype Wave Energy Converters (WECs) are typically moored as a single unit. Commercial installations of WECs are likely to comprise groups of devices, moored as wave energy 'farms' or arrays. The capital cost of the mooring hardware and installation cost can be a significant portion of the total capital expenditure, for a project including an array of WECs.

This study pushed the boundary of mooring design to investigate interconnected WECs in an array and as clusters of standalone units. MCS Kenny gained a leading edge for future design of mooring systems for commercial wave energy farms throughout this project.



## 2. PROJECT DESCRIPTION

Although similar to mooring systems used in the offshore oil and gas industry, moorings systems for WECs present some additional design challenges. To-date, there is limited clear guidance available for the design of mooring systems for WECs.

This project provided the means to evaluate and select a preliminary mooring system at an early design stage. This approach enables a designer to save time by evaluating preliminary mooring designs at an early stage of the WEC development, and thus the WEC and mooring system can be optimized in parallel for maximum power generating efficiency.

The scope of this research was as follows:

1. Perform a review the wave energy industry to define the range of potential design parameters, including WEC type and size, water depth, environmental conditions;
2. Perform hydrodynamic analysis to obtain the motion characteristics (A range of generic cylinders were selected to represent the range of WECs currently being developed);
3. Perform a review and compare the relevant design codes and guidelines. The codes currently being used in the wave energy industry for mooring are generally those used by the offshore oil and gas industry;
4. Investigate a range of mooring system configurations. The configurations selected were:
  - Catenary
  - Catenary with Rope
  - Surface Buoy
  - Surface Buoy with Clump Weights
  - Surface Buoy with Vertically Loaded Anchors
  - Compliant
5. Generate mooring stiffness curves for each mooring configuration in water depths ranging from 50m to 200m. The number of mooring lines in each layout was also varied;
6. Perform a dynamic analysis of the configuration using Ariane-3Dynamic and Flexcom (These configurations are illustrated in Appendix III);
7. Perform a preliminary fatigue life assessment of each configuration; and
8. Perform a risk assessment and failure mode assessment; and compile a preliminary monitoring and inspecting strategy.

The work performed on the project resulted in the following reports:

- DP01      Design Premise – Outlines the scope of work, methodology and design inputs.
- SR01      Study Report 01, Wave Energy Industry Review – Presents a review of the wave energy industry and WECs currently being developed.
- SR02      Study Report 02, Mooring System Design – Presents the stiffness curves and results from the dynamic mooring analysis.
- SR03      Study Report 03, Integrity Management Strategy – Presents the failure mode assessment, risk assessment and inspection/monitoring strategy.

### 3. RESULTS AND OUTCOMES

The “Mooring System Design” report (SR02) presents details of the different mooring line configurations which have been considered, the different components and materials used in mooring systems; and their approximate costs.

Extensive research and analysis was performed on a range of mooring configurations suitable to WECs in order to determine a methodology and applicable tool for preliminary sizing of mooring systems for early design stages. This was done by developing a set of design curves including stiffness curves and dynamic analysis results. Stiffness curves were compiled for various mooring configurations, water depths, chain lengths and chain diameters.

An example of a stiffness curve generated in this stage is presented in Figure I. The stiffness curve consists of two plots, which can be used to determine the feasibility of a given configuration. The bottom half of the graph in Figure I plots restoring force against WEC excursion. The top half plots tension in the most loaded line against WEC excursion. Using the combination of these curves, the feasibility of the given configuration can be estimated. The WEC excursion (offset) from current and wave loading can be estimated, as well as the resulting tension in the lines.

The legend for the stiffness curves is presented below the plot. The three different colours represent different chain sizes. The horizontal coloured lines indicate the breaking load of each chain size.

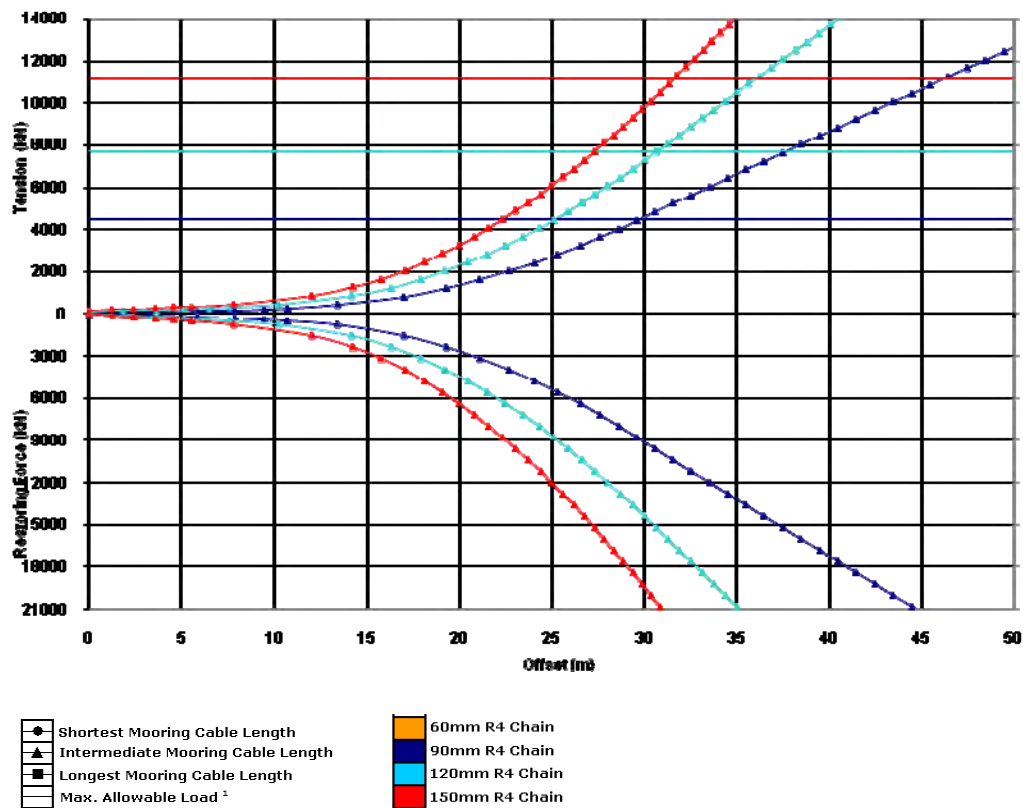
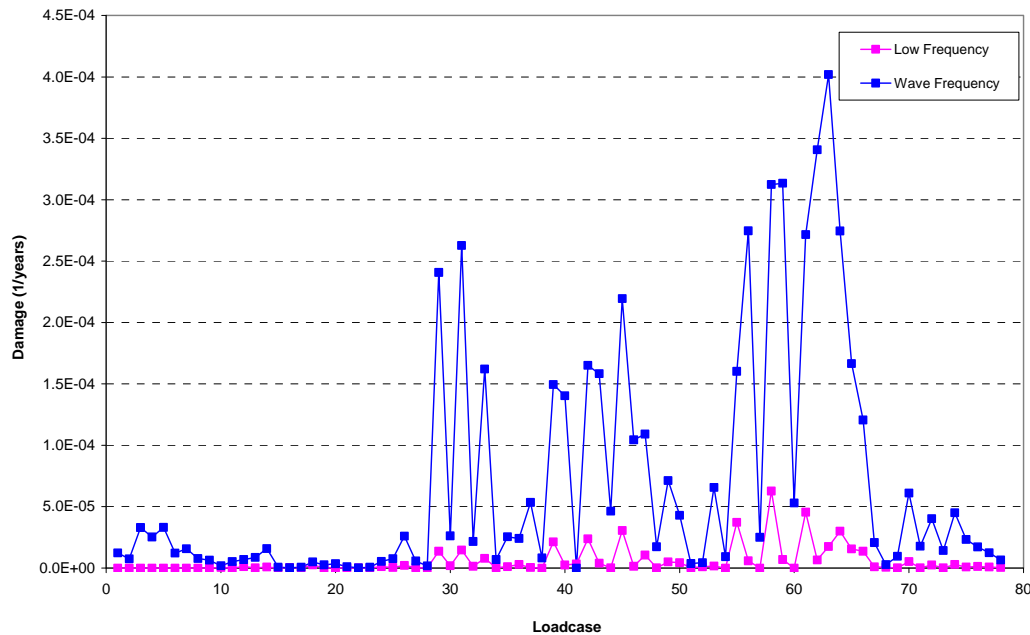


Figure 1: Mooring Line Stiffness Curve

Dynamic analysis was performed for intact (normal) and damaged (1 line broken) conditions for each configuration, for a range of environmental conditions. Fatigue, coupled analysis and layout of arrays were also evaluated.

Fatigue was found to be an important factor in the design of mooring systems for WECs. Wave energy farms will be located in areas with large wave heights all year round, which can cause significant fatigue damage. An example of a fatigue life plot is shown in Figure 2. The fatigue damage from long term loading is plotted, for low frequency and wave frequency conditions.

The calculated fatigue life of chain can vary from less than 10 years to more than 200 years depending on the configuration. Based on current experience in the oil and gas industry, fatigue of synthetic rope is expected to be more favourable than fatigue of chain.



**Figure 2: Example of Fatigue Life Plot**

If the mooring system exerts significant loads on the WEC in its operational condition, it may affect the motion of the WEC and reduce the efficiency of converting the energy from the waves to electrical energy. Coupled analysis can be used to assess the effect of the mooring system on the motions of the WEC. The requirements and benefits for coupled analysis are discussed in SR02.

It was found that the loading imposed on a WEC by a mooring line can be greatly reduced by careful material selection. For example, introducing synthetic rope into a mooring to replace some of the chain can provide increased elasticity to the line thus reducing loads by up to 20%. Reducing loads reduces the need for very strong and heavy components, which in turn may significantly reduce the cost of the mooring line.

Although configurations involving surface buoys have the advantage of minimal vertical loading on the WEC they also tend to allow larger excursions than a conventional catenary configuration. The excursion limit of a WEC is an important design consideration as it could be in close proximity to other WECs and the maximum excursion will be especially important with regard to the design of any electric/hydraulic power cables.

The cost of mooring line materials such as chain and wire/synthetic rope is discussed to give an idea of the cost of a mooring package. Mooring line accessories such as anchors and shackles are included in this discussion. The cost of mooring systems can be quite significant and should be reviewed at the design stage for various configurations.

The ultimate result of this project is the delivery of a comprehensive design tool for WEC mooring. The following flowchart in Figure 3 gives an overview of the design process:

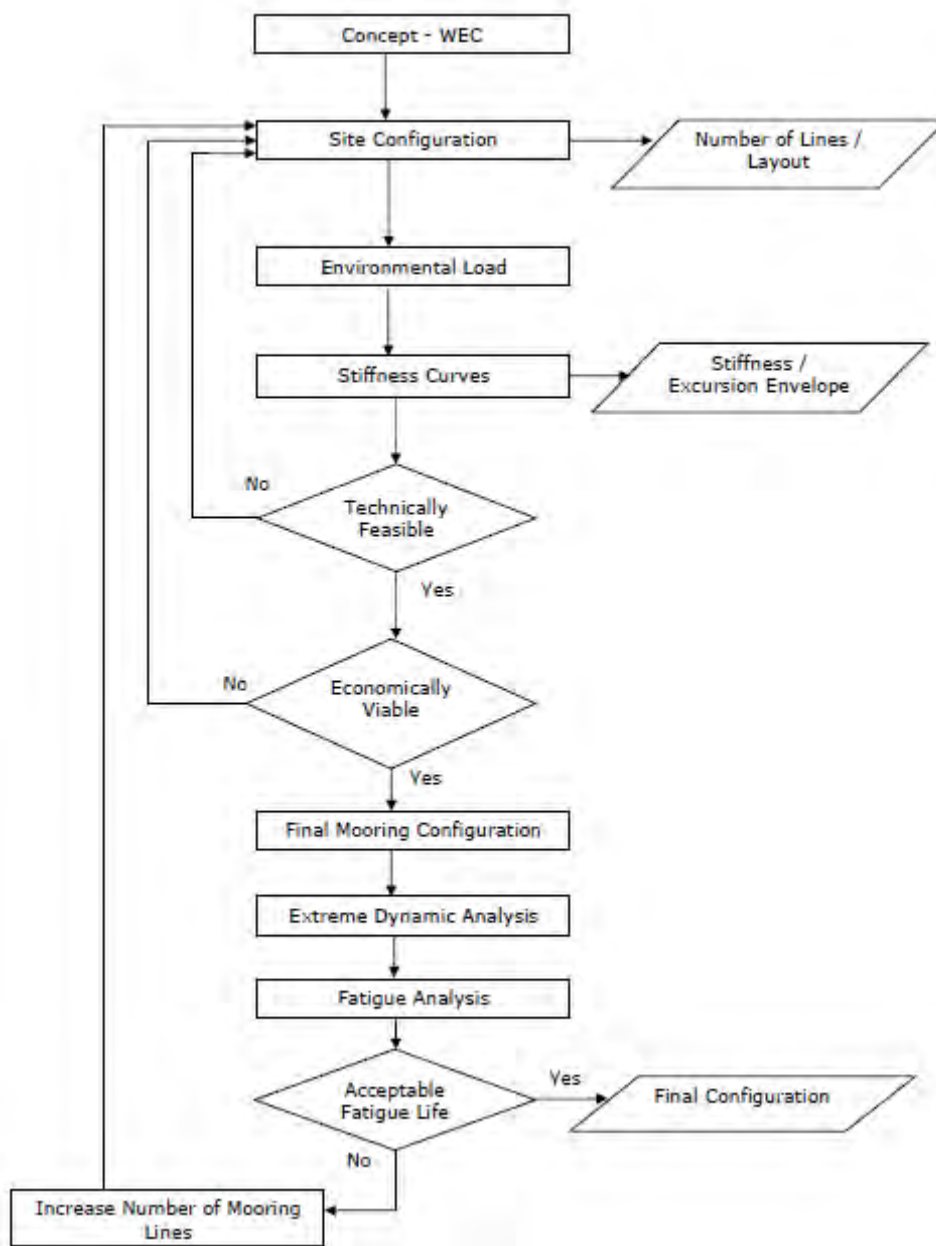
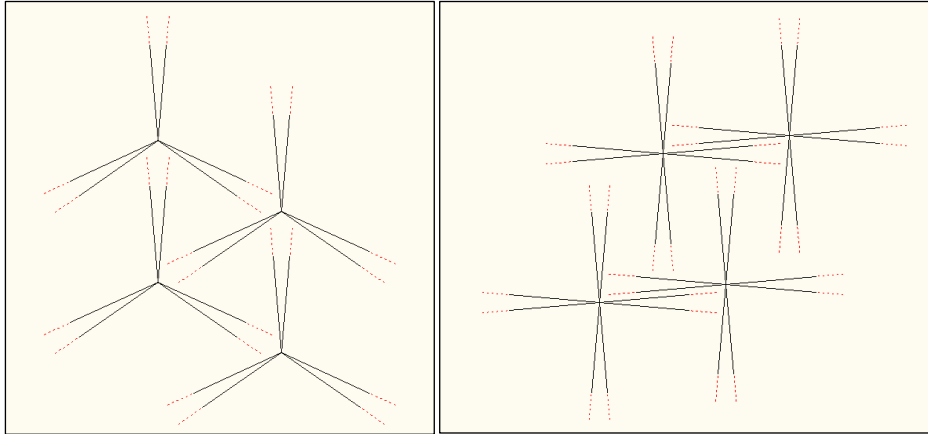
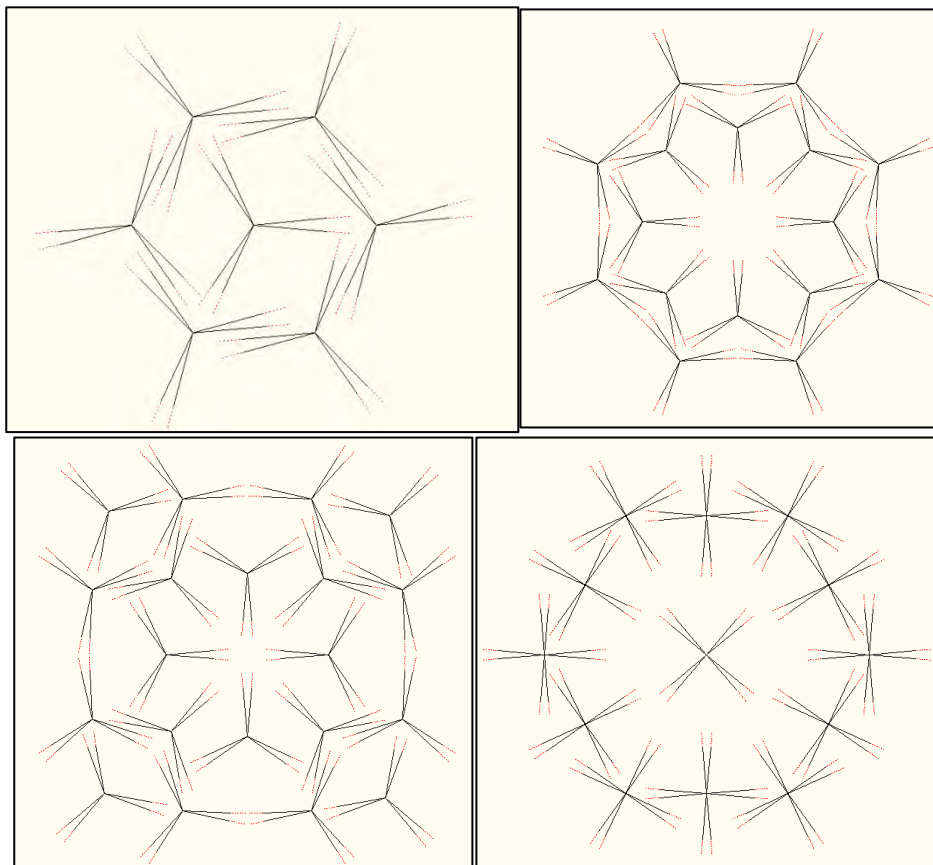


Figure 3: Mooring System for Wave Energy Arrays Design Process

Analysis was carried out to optimize the seabed footprint and components utilised by an array of WECs. Figure 4 shows WECs laid out in a grid formation, while Figure 5 shows examples of a radial layout. The optimum layout depends on the seabed topography, seabed infrastructure (electrical cables, etc.), ease of maintenance and repair, and the effect on the power generating efficiency of neighbouring WECs.

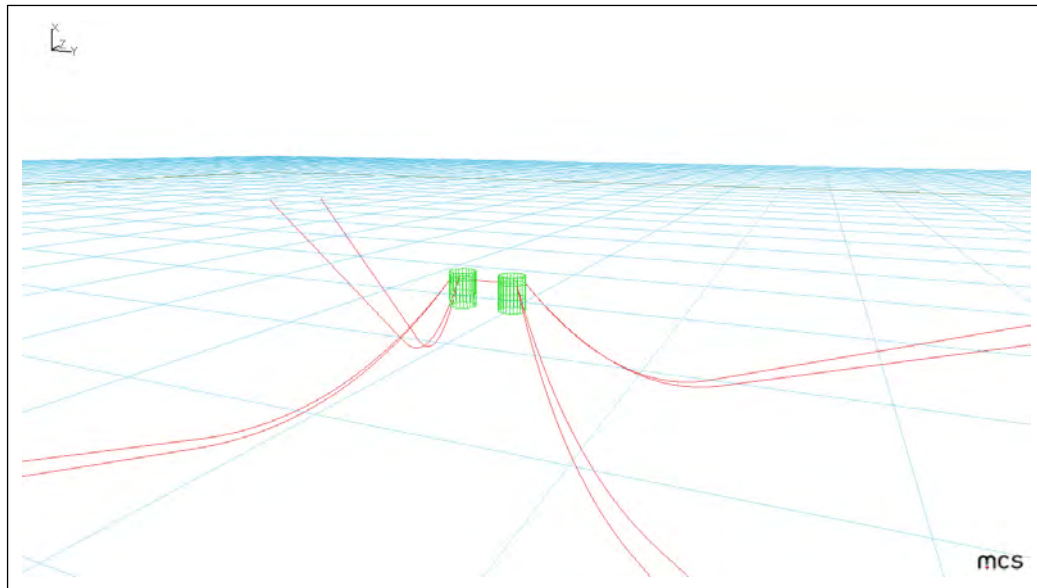


**Figure 4: Grid Array Optimization Examples**



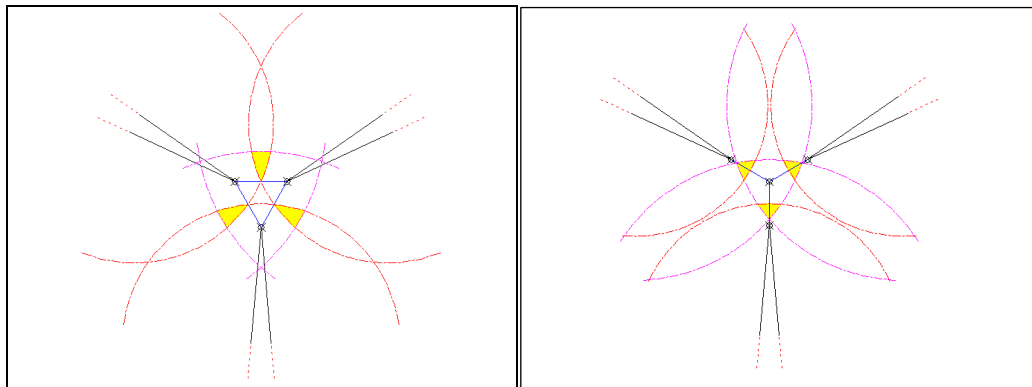
**Figure 5: Radial Array Optimization Examples**

Analysis was also carried out to investigate WECs interconnected in an array. A finite element model of two WECs connected to form a simple array is presented in Figure 6.



**Figure 6: WECs Connected in an Array**

Figure 7 shows WECs connected in a triangular array. The highlighted yellow areas show locations of possible clashing between WECs. The separation distance can be increased or the mooring system stiffness can be increased to eliminate the possibility of WEC's clashing with each other.



**Figure 7: Connected Wave Energy Array Optimization Examples**



The project provides a model for building an integrity management strategy. The integrity management strategy includes a risk assessment, a failure mode evaluation and describes the monitoring/inspection of a mooring system.

The “Integrity Management Strategy” report (SR03) reviews the risks to the Wave Energy Converter operation that are associated with failure of the mooring system or of a mooring line component. Guidelines for defining an Integrity Management Strategy to address and mitigate these risks have been developed in SR03. The guidelines in this report are based on the experience of MCS Kenny of the offshore oil and gas industry. Because a mooring system is mostly, and in some cases completely, under the water, its condition, and any maintenance or repair that may be required is difficult and costly to assess/undertake. To minimise maintenance and repair, sufficient attention should be given to the ongoing confirmation of the suitable operating condition of the mooring system. This is typically achieved by defining an Integrity Management Strategy. Installation of mooring systems is also considered in SR03.

## 4. IMPACTS AND BENEFITS

Funds from the Marine Institute enabled the company to apply its engineering development skills into a new but related marine engineering area; offshore wave energy generation. The work carried out in this research project give MCS Kenny a leading edge in mooring design for WECs. As a result, MCS Kenny is now in a prime position to support wave energy developers, operators and researchers in Ireland and elsewhere to design mooring systems. The project demonstrated the potential to standardise the approach to WEC mooring design. MCS Kenny believes that mooring systems will represent a key factor in the feasibility, operation, cost and functionality of WECs.

MCS Kenny has benefited from this project through research and gaining experience in a new energy development area. Time spent on designing and researching for a specific mooring design project can potentially be greatly reduced through the design tools developed in this project. New contacts have been established and intense technology has been generated.

Through this project, MCS Kenny is well positioned to expand its design consultancy services into a new, potentially high growth area, wave energy converter design. Importantly, this project positions the company as a key player in Ireland's renewable energy sector. It also allows the company to deploy this expertise in emerging international markets.

In Summary:

- The project has led to a WEC mooring design approach;
- Highlights the importance of mooring systems on how WECs and their moorings behave holistically;
- Training and technology has been gained as a result of this project;
- Future mooring projects, especially of WECs will benefit from the research carried out in this project.
- The company has gained expertise that will support new the development of business activity.

## APPENDIX I: COMPANY DESCRIPTION

MCS Kenny, a subsidiary of Wood Group, is a consulting engineering firm who specialise in delivering engineering solutions to the offshore energy sector. MCS Kenny provides engineering design services and also develops software for use in the design of dynamic slender offshore structures such as mooring lines, risers and umbilicals. The involvement of MCS Kenny in offshore developments spans all phases of design from conceptual and feasibility design, through to detailed design, installation and operations. MCS Kenny has traditionally provided services primarily to the oil and gas industry, more recently MCS Kenny extended its involvement in mooring system design for wave energy devices in keeping with the company's business expansion and given the significant business potential for MCS Kenny in the area.

## APPENDIX II: SOFTWARE DESCRIPTIONS

Ariane-3Dynamic is a time and frequency domain analysis program for analysis of mooring systems. Ariane-3Dynamic, developed by Bureau Veritas in collaboration with MCS Kenny, is the ideal tool for the design and analysis of moored vessels to current regulatory standards.

Wamit is a radiation/diffraction panel program developed for the linear analysis of the interaction of surface waves with offshore structures. Wamit has gained widespread recognition for its ability to analyse complex structures with a high degree of accuracy and efficiency.

Flexcom is a general purpose, nonlinear, three-dimensional, finite element package for the analysis of a wide range of slender offshore structures developed by MCS Kenny. The finite element used in Flexcom is a highly robust hybrid beam element, which can be used for modelling line type structures from fully compliant mooring lines to rigid risers. Flexcom has been validated against other finite element software and is generally recognised as the industry standard for riser analysis and configuration design.

## APPENDIX III MOORING CONFIGURATIONS

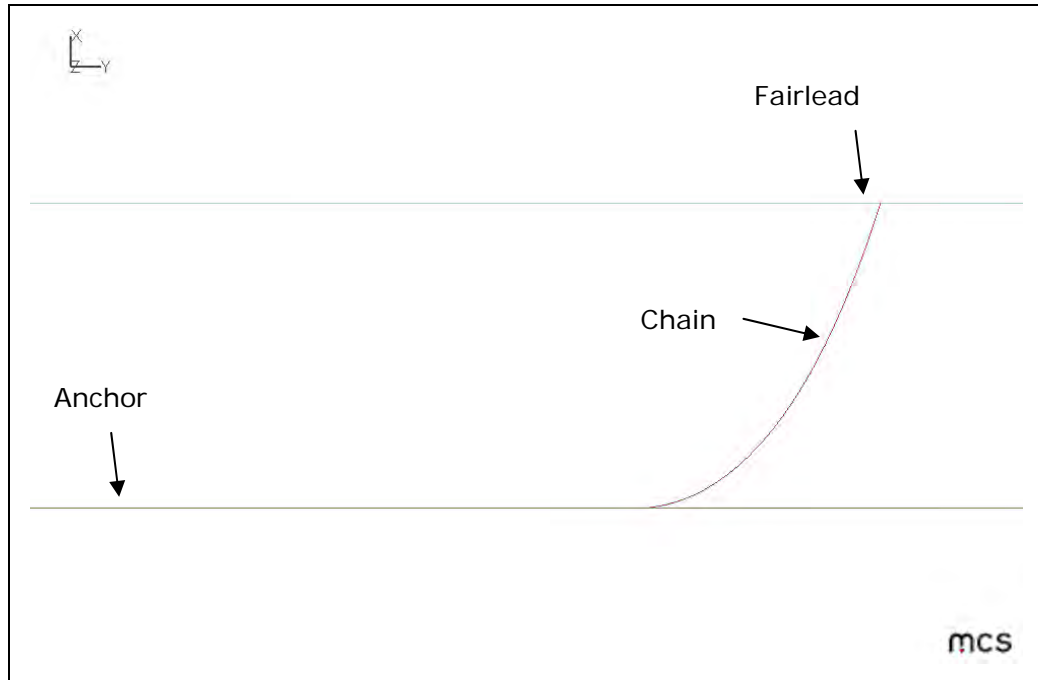


Figure 8: Catenary Configuration

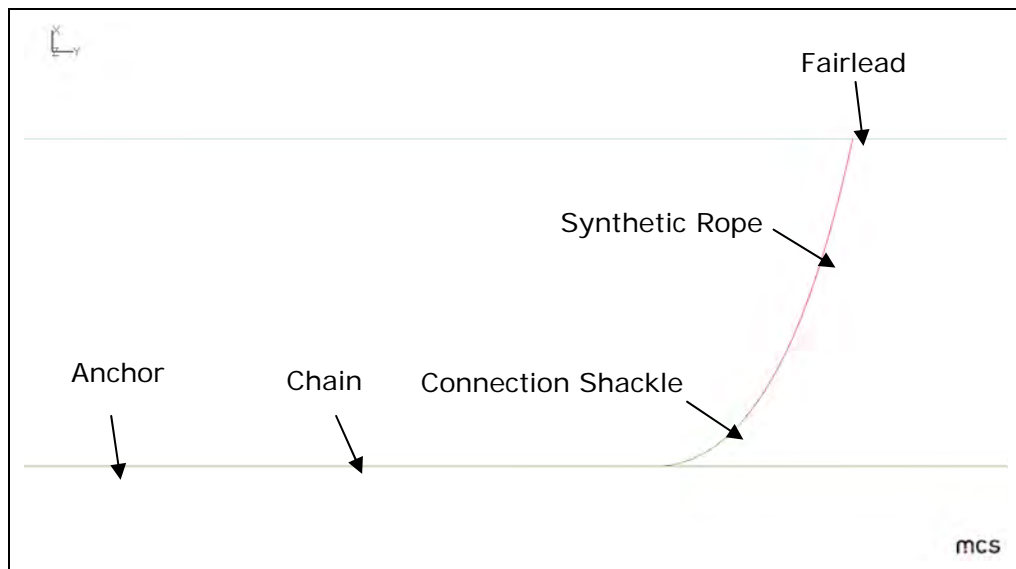
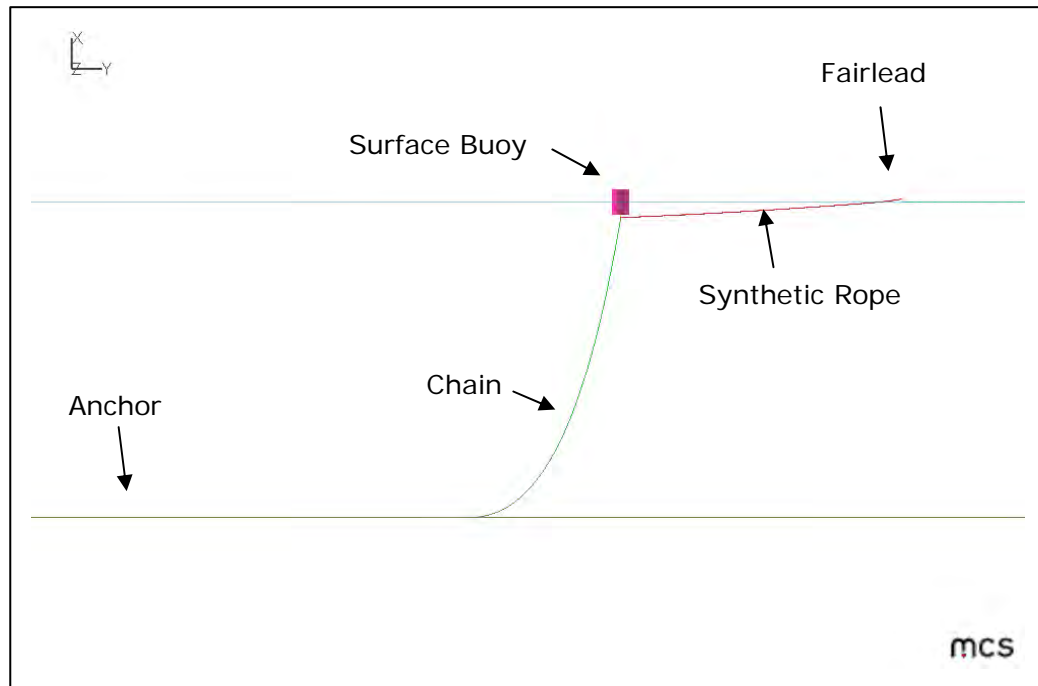
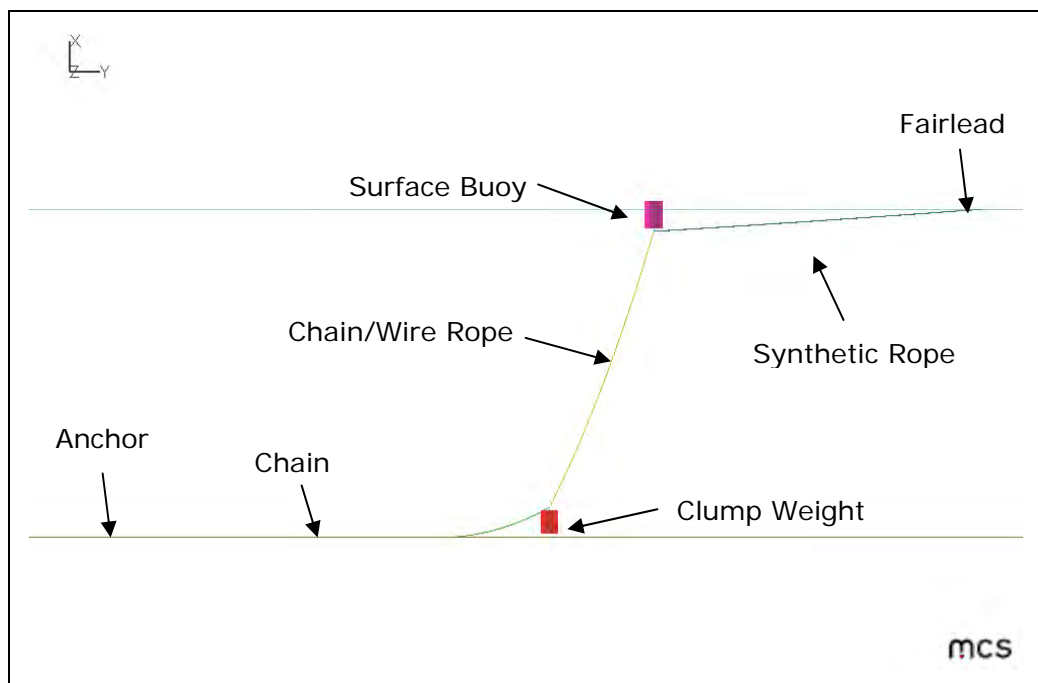


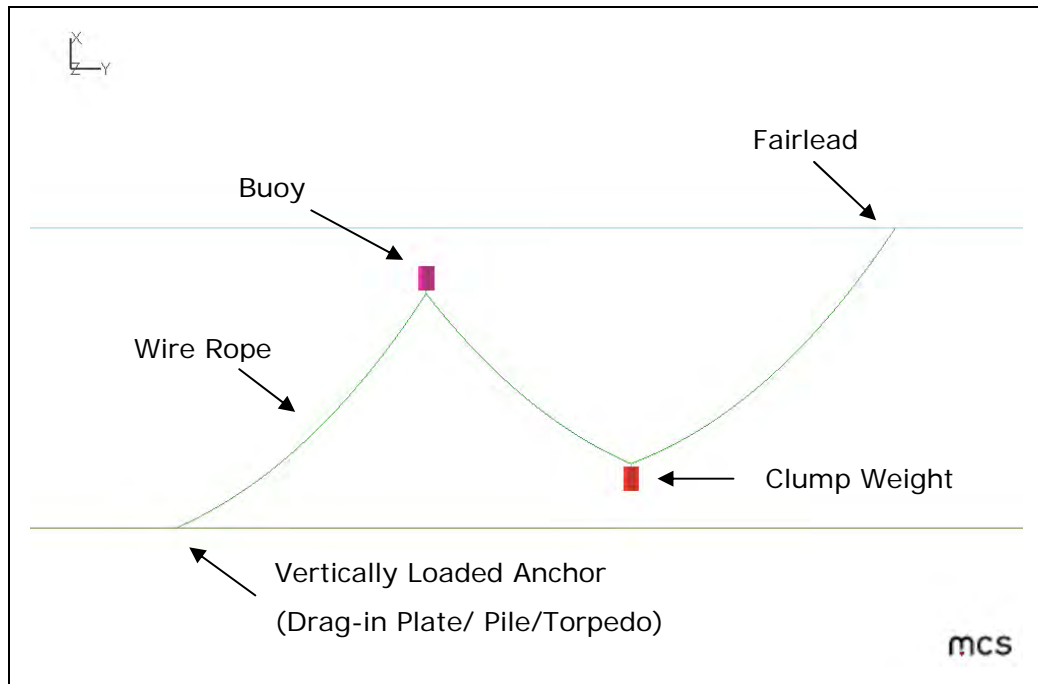
Figure 9: Catenary with Rope Configuration



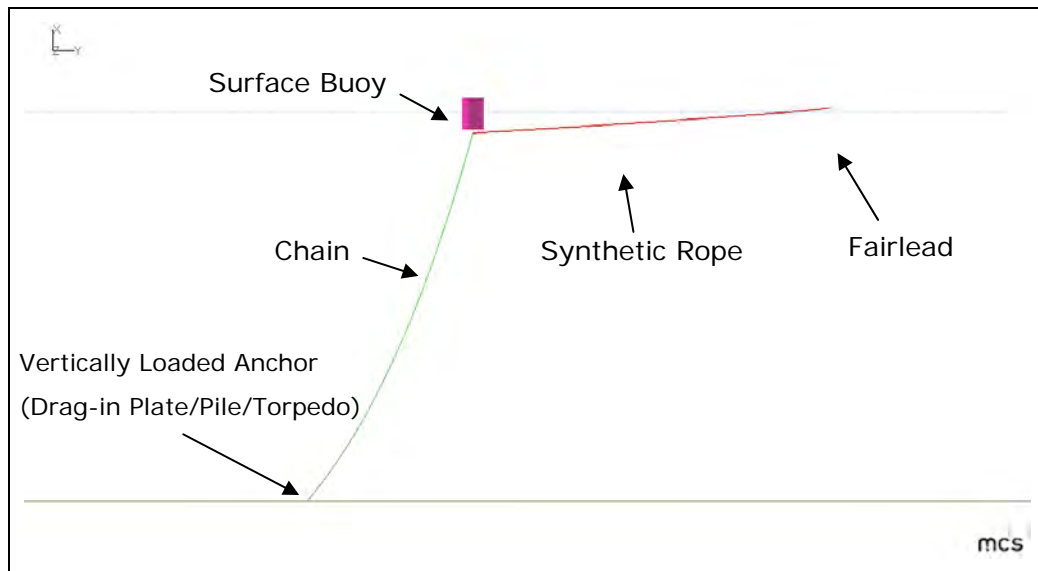
**Figure 10: Surface Buoy Configuration**



**Figure 11: Surface Buoy with Clump Weight Configuration**



**Figure 12: Compliant Configuration**

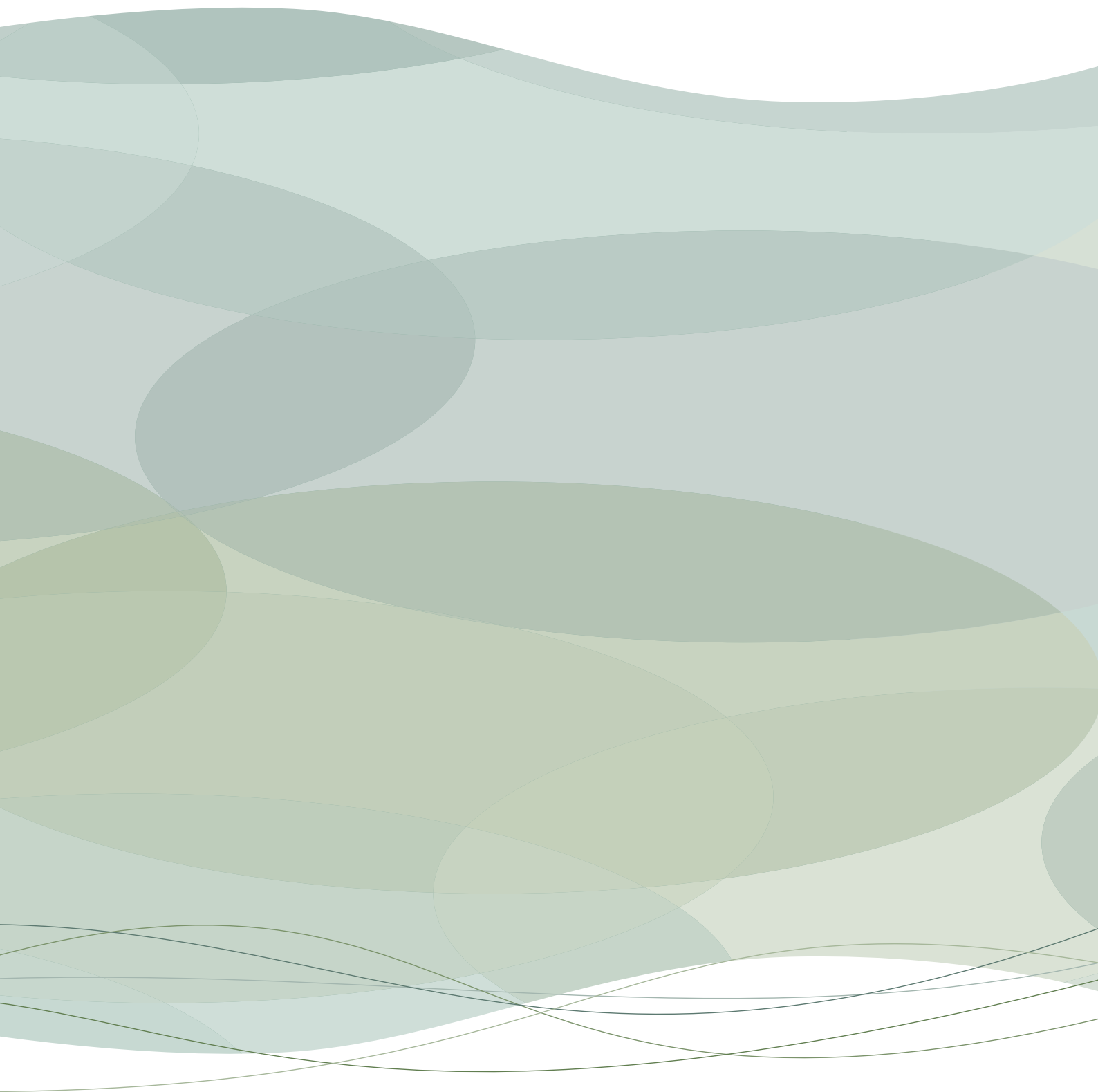


**Figure 13: Surface Buoy Configuration with Vertically Loaded Anchors**









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**Headquarters**

Marine Institute  
Rinville  
Oranmore  
Co. Galway  
Tel: +353 91 730 400  
Fax: +353 91 730 470  
Email: [institute.mail@marine.ie](mailto:institute.mail@marine.ie)

**Marine Institute Regional Offices & Laboratories**

Marine Institute  
80 Harcourt Street  
Dublin 2  
Tel: +353 1 476 6500  
Fax: +353 1 478 4988

Marine Institute  
Furnace  
Newport  
Co. Mayo  
Tel: +353 98 42300  
Fax: +353 98 42340